Online krypton and radon removal
for the XENON1T experiment

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for the XENON collaboration
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ONE
XENON1T

TWO
CRYOGENIC DISTILLATION

THREE
ONLINE KR REMOVAL

FOUR
RN REMOVAL
Enlightening the dark –
XENON Dark Matter Project and beyond

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~50 000 kg

~10^{-49} cm²

Michael Murra - Online krypton and radon removal for the XENON1T experiment – XeSAT 2017 Khon Kaen
## Enlightening the dark – XENON Dark Matter Project and beyond

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See talk by Dr. J. Naganoma

Michael Murra - Online krypton and radon removal for the XENON1T experiment – XeSAT 2017 Khon Kaen
Background of XENON1T has to be reduced by 2 orders of magnitude w.r.t. XENON100
Intrinsic contamination by $^85\text{Kr}$

Leakage events from the low energy $\beta$-spectrum with long half-life contaminate ROI for dark matter search

Commercial xenon:

$^{\text{nat}}\text{Kr}/\text{Xe} \sim 10^{-9} - 10^{-6}$ (ppb – ppm)

$^{85}\text{Kr}/^{\text{nat}}\text{Kr} \sim 2 \times 10^{-11}$

$^{85}\text{Kr}/\text{Xe} \sim 2 \times 10^{-20} - 2 \times 10^{-17}$

For XENON1T:

$^{\text{nat}}\text{Kr}/\text{Xe} < 2 \cdot 10^{-13}$ (0.2 ppt) $\leftrightarrow$ 0.2 $\frac{\text{evt}}{\text{y} \cdot \text{ton}}$

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$^{85}\text{Kr}-\text{tagging in XENON1T by delayed coincidence analysis}$

ppm = parts per million

ppb = parts per billion

ppt = parts per trillion

ppq = parts per quadrillion
Intrinsic contamination by $^{222}\text{Rn}$

Leakage events from the low energy $\beta$-spectrum contaminate ROI for dark matter search

Continuously emanating from detector material, getters, pumps, etc...:

$\rightarrow$ Material selection
$\rightarrow$ Continuous removal

In XENON100:
$\text{Rn}/\text{Xe}$: $\sim 45 \mu\text{Bq/kg} \approx 4.5 \cdot 10^{-24}$

For XENON1T:
$\text{Rn}/\text{Xe}$: $\sim 10 \mu\text{Bq/kg} \approx 1.0 \cdot 10^{-24}$

See talk by P.A. „Sander“ Breur

See talk by P.A. „Sander“ Breur

Michael Murra - Online krypton and radon removal for the XENON1T experiment – XeSAT 2017 Khon Kaen
XENON1T:

Goal for 2 ton x year exposure:

\[ \text{natKr/Xe} < 2 \cdot 10^{-13} \text{ (0.2 ppt)} \]

\[ ^{222}\text{Rn/Xe} = 10 \, \mu\text{Bq/kg} \]
Principle and Design

Difference in vapor pressure:
relative volatility: $\alpha = \frac{P_{Kr}}{P_{Xe}} \approx 10.5$ at 178 K

Multi-stage DST with partial reflux:

Krypton as the more volatile gas is collected at the top

Single Stage DST:

Package column:

McCabe – Thiele diagram:
The XENON1T column

Design Parameter
(Performance after commissioning at XENON1T):

Feeding flow rate: 8.3 SLPM (3kg/h)  
→ Thermodynamically stable up to 18 SLPM (6.5kg/h)

Separation factor: $10^4$ – $10^5$  
→ measured separation = $6.4 \cdot 10^5$

Kr removal: $^{nat}\text{Kr}/\text{Xe} < 0.2 \cdot 10^{-12} = 0.2$ ppt  
→ $^{nat}\text{Kr}/\text{Xe} < 0.048 \cdot 10^{-12}$ (48 ppq)  
→ Lowest in Muenster: $^{nat}\text{Kr}/\text{Xe} < 0.026 \cdot 10^{-12}$ (26 ppq)

Xe recovery: 99%  
→ Achieved

References:

JINST 9 (2014) P10010  
arXiv:1612.0428, accepted by EPJ C
Offline distillation

Start: $^{nat}\text{Kr}/\text{Xe} \approx 50 \text{ ppb}$

Goal: $^{nat}\text{Kr}/\text{Xe} < 0.2 \text{ ppt}$

ReStoX (RSX)
XENON Storage
3.2 t

Distillation (DST)
Remove Kr with 3 kg/h (6.5 kg/h)

Cryostat
Housing TPC

Kr removal in 44 days (21 days)
Offline distillation

Start: $\text{natKr/Xe} \approx 50 \text{ ppb}$

Goal: $\text{natKr/Xe} < 0.2 \text{ ppt}$

ReStoX (RSX)
XENON Storage
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Distillation (DST)
Remove Kr with 3 kg/h (6.5 kg/h)

Cryostat
Housing TPC

Kr removal in 44 days (21 days)

But what do you do, when the cryostat is filled already?!?

$\rightarrow$ Recover, warm-up, pump, distill, reach purity

TOTAL: order 90 days, 3 month downtime
**XENON1T:**

Goal for 2 ton x year exposure:

\[ ^{\text{nat}}\text{Kr}/\text{Xe} < 2 \cdot 10^{-13} \text{ (0.2 ppt)} \]

\[ ^{222}\text{Rn}/\text{Xe} = 10 \mu\text{Bq/kg} \]

---

**Cryogenic distillation:**

Krypton as the more volatile gas is collected at the top

- stable up to 18 SLPM (6.5 kg/h)
- measured separation = \(6.4 \cdot 10^5\)
- \(^{\text{nat}}\text{Kr}/\text{Xe} < 0.048 \cdot 10^{-12} \text{ (<48 ppq)}\)

---

**THREE**

**ONLINE KR REMOVAL**

---

**FOUR**

**RN REMOVAL**
Online Kr distillation

TPC as single DST stage:

Gas phase (GXe)

Kr enriched offgas

3.50 slpm

Distillation (DST)
Remove Kr from gas phase of TPC

0.04 slpm

Liquid phase (LXe)

Purification (PUR)
Remove electro-negatives continuously

3.50 slpm*

3.46 slpm

49.96 slpm

46.50 slpm

* Limited flow by flow controllers at cryogenic system
Distillation (DST)
Remove Kr from gas phase of TPC

Kr enriched offgas

Purification (PUR)
Remove electro-negatives continuously

Disturb Kr equilibrium between GXe and LXe

Remove Kr from GXe

Kr migrates from LXe into GXe

* Limited flow by flow controllers at cryogenic system

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Results

Effectively: 70 days
But TPC online, in parallel:
- Kr\(^{83}\)m calibrations
- Rn\(^{220}\) calibrations
- NR calibrations
- Purity increase
- PMT tests
- DAQ tests
- Finish commissioning
- Reached sufficient Kr level for first science run!

\(\text{nat}^{\text{Kr}}/\text{Xe} = 0.62 \text{ ppt}\)
**XENON1T:**

Goal for 2 ton x year exposure:

\[ ^{222}\text{Rn}/\text{Xe} = 10 \ \mu\text{Bq/kg} \]

\[ ^{136}\text{Kr}/\text{Xe} < 2 \cdot 10^{-13} \ (0.2 \ \text{ppt}) \]

**Cryogenic distillation:**

- Krypton as the more volatile gas is collected at the top
- stable up to 18 SLPM (6.5 kg/h)
- measured separation = $6.4 \cdot 10^5$
- $^{136}\text{Kr}/\text{Xe} < 0.048 \cdot 10^{-12} (<48 \ \text{ppq})$

**Online Kr removal:**

- Remove Kr from GXe
- Disturb Kr equilibrium between GXe and LXe
- Kr migrates from LXe into GXe

**First Science Run:**

\[ ^{136}\text{Kr}/\text{Xe} = 0.62 \cdot 10^{-12} \ (0.62 \ \text{ppt}) \]
**Principle of Rn distillation**

**Inverse krypton mode**

**Difference in vapor pressure:**

Relative volatility: $\alpha = \frac{P_{Rn}}{P_{Xe}} \approx 0.1$ at 178 K

Radon as the **LESS** volatile gas is collected at the **bottom**

Radon trapped in LXe until desintegration

“off-gas” is radon depleted

No xenon loss

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Online Rn distillation
XENON100

- Total flow of 4.5 slpm (1.6 kg/h) through DST column
- Continuous removal
- Auxiliary emanation source to test reduction power of DST
- XENON100 as monitor of radon activity

Reduction inside XENON100: \( r = (22.4 \pm 0.8) \)

Reduction factor DST: \( R > 27 \) (90% C.L.)
Rn budget at XENON1T

- TPC: (4.8 ± 2.2) mBq (13.6%)
- inner vessel: (2.0 ± 0.3) mBq (5.6%)
- getter: (1.5 ± 0.1) mBq (4.2%)
- cryo pipe: (9.2 ± 1.0) mBq (26.0%)
- cryo system: (2.4 ± 0.3) mBq (6.8%)
- 100mm pipe + cables: (2.7 ± 0.2) mBq (7.6%)
- porcupine: (1.9 ± 0.2) mBq (5.4%)
- QDrive pumps: (10.9 ± 1.7) mBq (30.8%)

Total: 37.4 mBq (CRY: 16.4 mBq (43.8%) and PUR: 14.6 mBq (39%))
Cryogenic system emanates 46% of total budget
Cryogenic system emanates 46% of total budget

Purification system emanates 35% of total budget

Rn budget at XENON1T

Cryogenic system
- cryo pipe: (9.2 ± 1.0) mBq (26.0%)
- 100mm pipe + cables: (2.7 ± 0.2) mBq (7.6%)
- porcupine: (1.9 ± 0.2) mBq (5.4%)
- cryo system: (2.4 ± 0.3) mBq (6.8%)

Purification system
- TPC: (4.8 ± 2.2) mBq (13.6%)
- inner vessel: (2.0 ± 0.3) mBq (5.6%)
- QDrive pump: (10.9 ± 1.7) mBq (30.8%)
- 5.6%
Online Rn distillation at XENON1T

TPC as single DST stage:

Gas phase (GXe)

Kr enriched offgas

Distillation (DST)
Remove Kr from gas phase of TPC

Purification (PUR)
Remove electro-negatives continuously

Liquid phase (LXe)

Kr

3.50 slpm

46.50 slpm

49.96 slpm

3.46 slpm

0.04 slpm
Online Rn distillation at XENON1T

TPC

Gas phase (GXe)

3.50 slpm

46.50 slpm

50.00 slpm

Liquid phase (LXe)

Purification (PUR)
Remove electro-negatives continuously

Distillation (DST)
Online Rn distillation at XENON1T

TPC

Gas phase (GXe)

Liquid phase (LXe)

Cryogenics (CRY)

Distillation (DST)

Purification (PUR)

Remove electro-negatives continuously

GXe

LXe

3.50 slpm

46.50 slpm

50.00 slpm

46.50 slpm

50.00 slpm

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Online Rn distillation at XENON1T

- **Cryogenics (CRY)**
  - Remove Rn continuously
  - 3.50 slpm*

- **Distillation (DST)**
  - Remove Rn from gas phase of CRY
  - 3.50 slpm

- **Purification (PUR)**
  - Remove electro-negatives continuously
  - Limited flow by flow controllers at cryogenic system

- **TPC**
  - Gas phase (GXe)
  - Liquid phase (LXe)

- **46.50 slpm**
- **50.00 slpm**
- **5.00 slpm**

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Online Rn distillation at XENON1T

- Extract and remove radon from GXe of CRY emanated by cryo-pipe and cables
- Less Rn can enter TPC

→ Total radon activity concentration inside TPC reduced without xenon loss

- Limited flow by flow controllers at cryogenic system
Results

Radon reduction in XENON1T by almost 20%

See talk by P.A. „Sander“ Breur

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**XENON1T:**

Goal for 2 ton x year exposure:

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**Online Kr removal:**

- Disturb Kr equilibrium between GXe and LXe
- Remove Kr from GXe
- Kr migrates from LXe into GXe

**First Science Run:**

\[
\text{nat} \text{Kr}/\text{Xe} = 0.62 \cdot 10^{-12} \text{ (0.62 ppt)}
\]

**Summary:**

**Cryogenic distillation:**

- Krypton as the more volatile gas is collected at the top
  - stable up to 18 SLPM (6.5 kg/h)
  - measured separation = \(6.4 \cdot 10^5\)
  - \(\text{nat} \text{Kr}/\text{Xe} < 0.048 \cdot 10^{-12} \text{ (<48 ppq)}\)

**Rn removal:**

- Radon as the less volatile gas is collected at the bottom
- Cryogenic Distillation can remove radon as shown in XENON100 \((R > 27)\)
- Radon reduction in XENON1T of 20% with continuous distillation without xenon loss